Probing the Circumgalactic and Intergalactic Media in the HabEx Era

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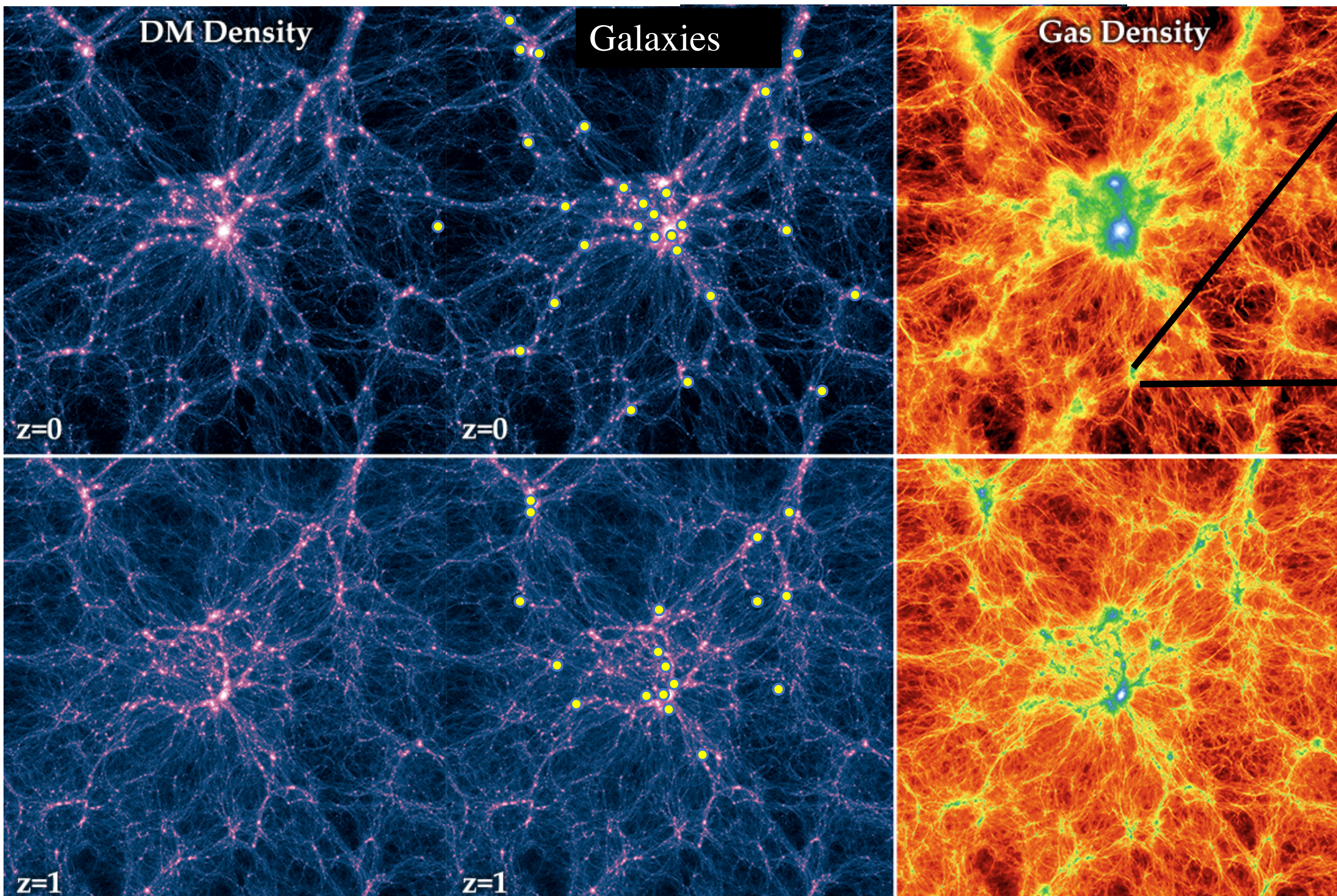
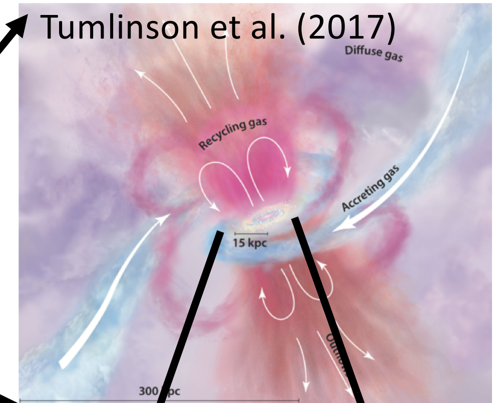
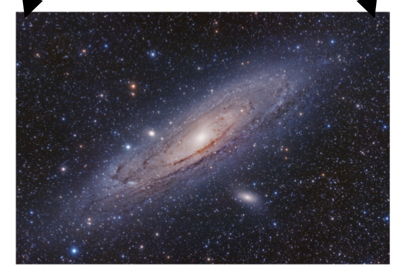
A Central Question

- The circumgalactic medium (CGM) and the intergalactic medium (IGM) host the vast majority of the baryons (~90%)
- The CGM refers to gas contained within dark matter halos
  - It extends from low mass galaxies to massive clusters (where it is known as the intra-cluster medium, or ICM)
- The IGM is the more widely distributed gas, not bound to a particular halo
- They are critical elements of galaxy evolution
  - Reflect the impact of feedback and serve as a gas reservoir for star formation
- They are important for cosmology
  - The baryon distribution affects the dark matter power spectrum (at least on small scales), and hence dark sector studies (e.g., Stage IV dark energy surveys)



Tumlinson et al. (2017)





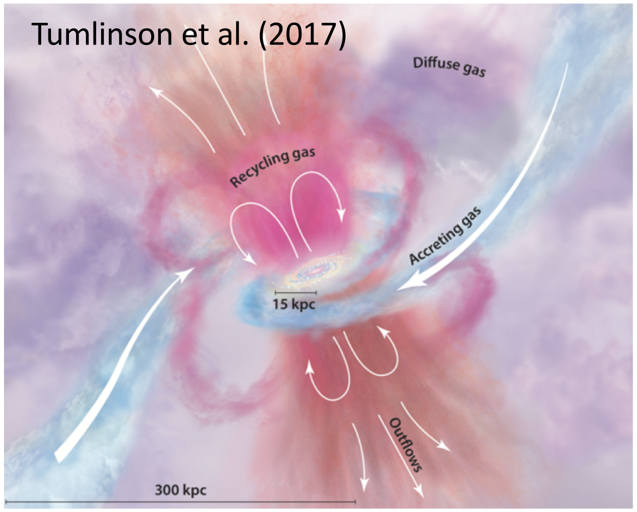
90% of the baryons are in the CGM/IGM that we know little about.

Focus on CGM: An Observational Challenge

- In clusters, the ICM has long been observed in X-rays and via the thermal Sunyaev-Zeldovich (tSZ) effect – *"Easy"*
- Much more difficult to observe in galaxy and group halos, but they contain most of the mass
  - Typical temperatures and densities: $10^4 K < T < 10^7 K \quad n \leq 10^{-3}\mathrm{cm}^{-3}$
  - Faint emission
- A number of observational probes at different wavelengths
  - We need a comprehensive approach combining these probes
  - HabEx will be one such element in the 2030s

Physical Properties To Be Measured

- Density and spatial distribution
- Ionization state
- Composition, i.e., metallicity
- Temperature(s)
- Multi-phase structure



- Relation of all above to host galaxy properties
- Relation of all above to feedback

Observational Probes and Methods

- Probes
  - X-ray emission
  - Spectral lines
    - Absorption against background sources
    - Emission
  - NEW: Thermal SZ (tSZ) and kinetic SZ (kSZ) effects

- Methods
  - Detailed study of individual objects
  - Statistical studies, e.g., cross-correlations and stacking

Observational Probes: 2030s

- X-ray emission
  - European Space Agency's *Athena* mission
- Spectral lines
  - Absorption: HabEx, …
  - Emission: large galaxy redshift surveys
- New: Thermal SZ (tSZ) and kinetic SZ (kSZ) effects
  - CMB-Stage 4 (CMB-S4), CMB-High Definition (CMB-HD), space mission (e.g., PICO)?

Observational Probes: 2030s

- X-ray emission and spectra
  - $\sim n_{\rm ion}^2 T_{\rm em}^{1/2}$ & $\sim T_{\rm em}$
- Spectral lines
  - Absorption: $\sim n_{\rm neu}$
  - Emission: $\sim n_{\rm ion}^2$ Ts
- New: tSZ and kinetic SZ (kSZ) effects
  - $\sim n_{\rm ion} T_{\rm mw}$ & $\sim \frac{v}{c} n_{\rm ion}$
- We can learn about densities, distributions, temperatures, ionization state and multi-phase structure

Considerations for Sample Selection

- How to distribute a given total observation time?
  1. Small sample, high S/N
  2. Large sample, low S/N and stacking/cross-correlations
- Arguments in favor of choice 2:
  - More representative sample for population trends
  - Divide into sub-samples to measure scaling relations
  - Spectral line observations only sample a finite number of sightlines (often 1) through an individual object
  - When using survey data (e.g., CMB), sensitivity is pre-set: must deal with low S/N

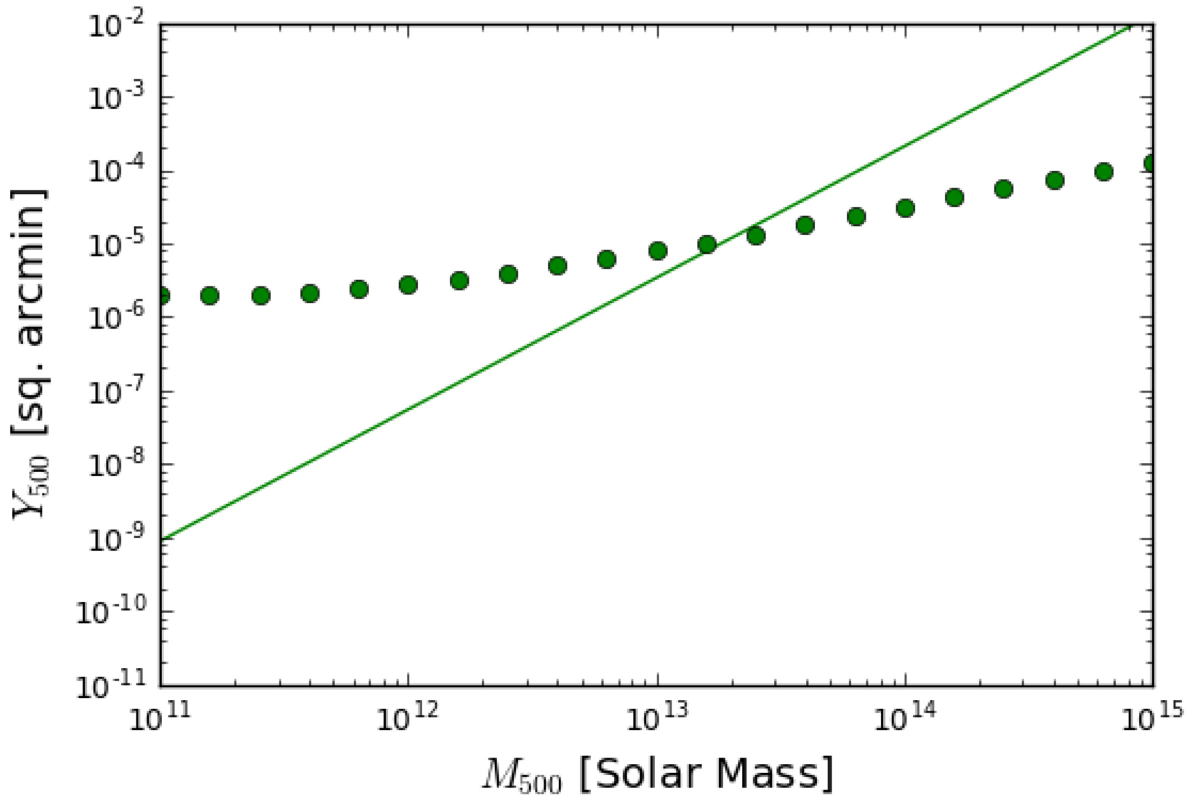
Example: Approach 2 - Sample with HabEx, CMB and X-ray

- Estimate size of HabEx sample for UV absorption line studies
  - Select galaxies at low z (Ly-alpha in UV)
  - Used ETC to estimate integration time to reach S/N~1 on ~1 background source per foreground galaxy
  - To reach S/N~1 at at R=3000 (100 km/s) on ~1 background source in HabEx field-of-view centered on foreground galaxy: mag_{FUV} =23AB based on FUV source counts
  - With 25% overhead: ~ 25mins/object
  - Program of 1000 objects requires ~416 hours
- Look at combining with other observations
  - CMB-S4 and possible CMB-HD instrument
  - X-ray: *Athena*

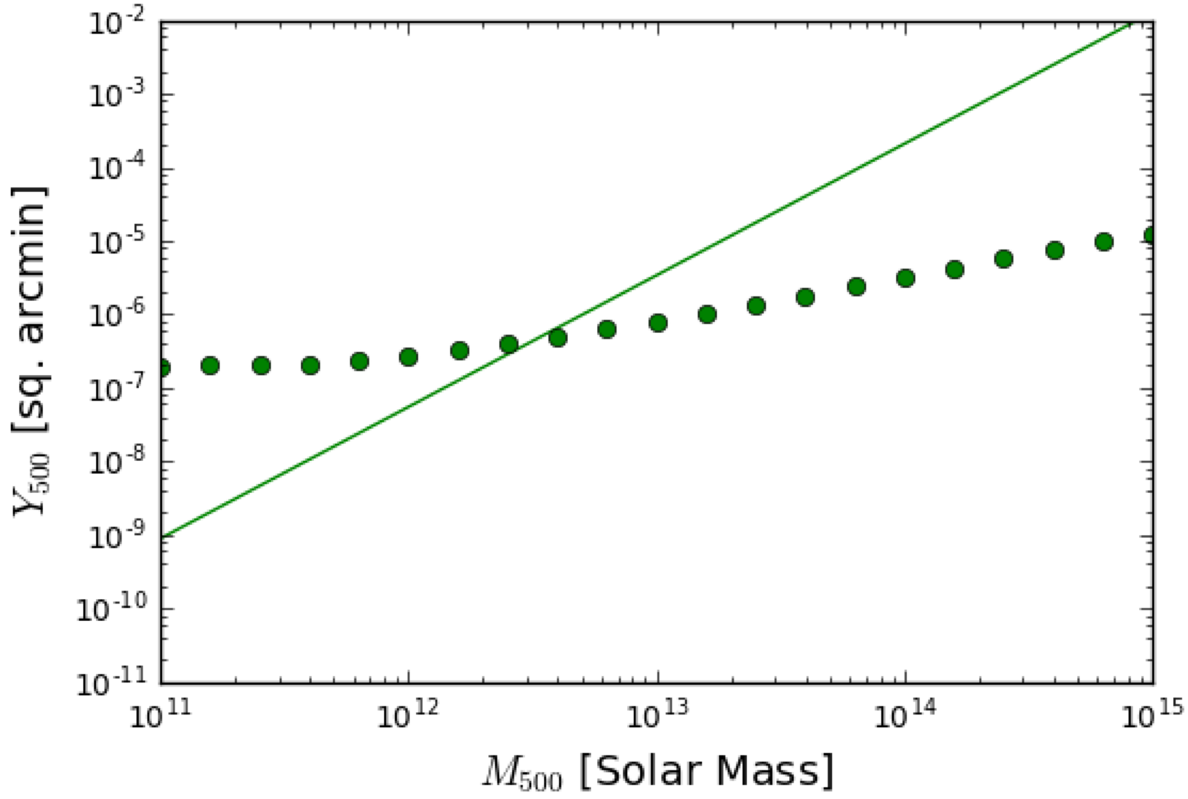
CMB-S4: tSZ sensitivity for galaxy-sized halos

- Survey
  - 40% of sky at 1.5 arcmin resolution to ~1 muK-arcmin sensitivity in 7 years
  - Start ~2025
- Dedicated point to go deeper:
  - 24 square degrees to 0.1 muK-arcmin sensitivity in 1 year
  - Could be proposed after main CMB-S4 survey

CMB-S4 Main Survey Sensitivity



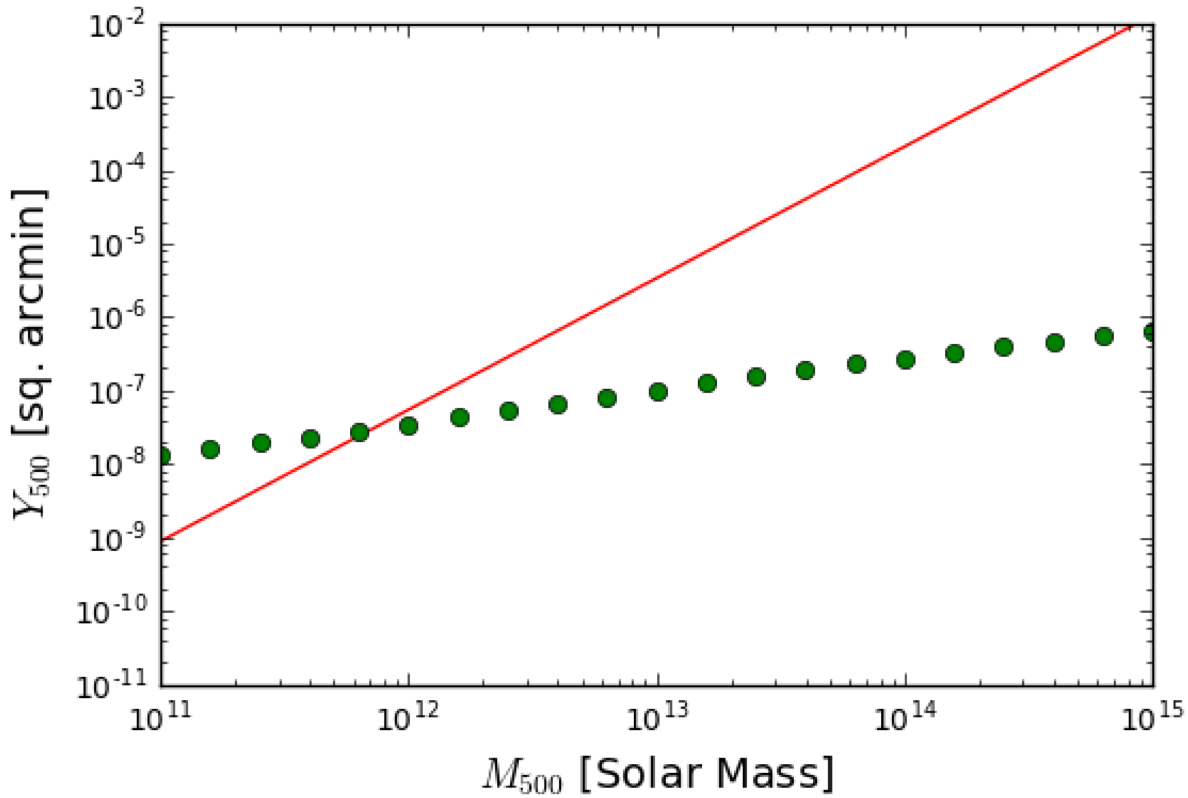
CMB-S4 Deep Survey Sensitivity



CMB-HD

- Instrument set-up
  - 95, 150, 220 GHz
  - 27, 20, 17 arcsec resolution
  - 0.15, 14, 0.36 muK-arcmin sensitivity over 10-100 square degrees

CMB-HD



10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
Y_{500} [sq. arcmin]
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
M_{500} [Solar Mass]

Conclusion

- The distribution and physical characteristics of the CGM/IGM is a central question in galaxy evolution and important for stage IV dark energy surveys
- Need a comprehensive observational approach across wavebands, observational probes and methodology
- HabEx will be a powerful element of such a program in the 2030s
- We're evaluating what can be learned by these kinds of comprehensive studies
- Toy example of HabEx sample with CMB and X-ray observations